Experimental study on change in mechanical and hydraulic characteristics of granular sub-base course of permeable pavements

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Abstract

When rainwater permeates into the ground, the granular materials in the sub-base course of the permeable pavements move, and their durability and water permeability undergo a change. In this research, we investigated the mechanical and hydraulic characteristics of the granular materials of permeable pavements. We carried out a laboratory test wherein specimens with a CBR values were watered and their properties before and after watering were investigated. We also conducted a field experiment involving rainfall simulation in an experimental yard.

1. Introduction

In recent years, Japanese cities have undergone rapid urbanization. In urbanized areas where the land is covered by houses, roads, etc., rainwater cannot infiltrate into the ground. This is one of the primary causes of urban flooding. To successfully deal with this phenomenon, comprehensive flood control systems are needed. One solution for the urban flooding problem is the use of permeable pavements.

The permeable asphalt pavements comprise a porous asphalt mixture and granular materials. The pavements can reduce direct runoff of rainwater from roadways, because they allow rainwater to permeate to the subgrade. The durability and permeability of permeable pavements are being investigated in laboratories and through field experiments.[1] The investigations reported that infiltration of rainwater reduces the durability and water permeability of the granular sub-base and the subgrade.[2] Some researchers confirmed decrease in the CBR after water percolation in some kind and gradation of granular sub-base materials.[3][4] They attributed the decrease in the CBR to seepage water, moving of fine aggregate, and changing of aggregate matrix.

In this research, rainfall simulation tests were carried out on permeable asphalt pavements with three different structures, and change in mechanical performance of the pavements between before and after watering were investigated by using FWD measurements. The stiffness of each layer was verified based on back-calculation of FWD measurements. Water percolation tests were also performed in laboratory for compacted sub-base materials, and permeability and CBR of them was examined. Change in permeability and CBR between before and after water percolation and the effect

of grain size distribution and compaction ratio is discussed in this paper.

2. Verification of change in bearing capacity of granular materials in the case of an actual road

A field experiment involving rainfall simulation was conducted in an experimental yard to verify the change in the bearing capacity of the granular sub-base due to seepage water.

(1) Experimental yard

a) Structures and materials of the pavements

Figure 1 shows the structure of the pavement constructed for the test. Four sections were prepared. Sections 1, 2 and 3 were permeable pavements and section 4 was a conventional impervious pavement. Section 4 was constructed using recycled dense-graded asphalt mixture for the surface and recycled crusher run (RC-40) for the granular materials. The base course of section 2 consisted of two layers: RC-40 was used for the base course and a recycled mechanically stabilized crushed stone (RM-40) was used as the sub-base course. Sections 1 and 3 contained a layer of sand as a filter layer. As sections 1, 2 and 3 are compared with section 4, the influence of the water permeating would be verified. Sections 1 and 3 are compared with section 2 to determine the effect of a filter layer. The characteristics of the asphalt mixtures, granular materials, and subgrade are listed in Tables 1, 2, and 3 respectively.

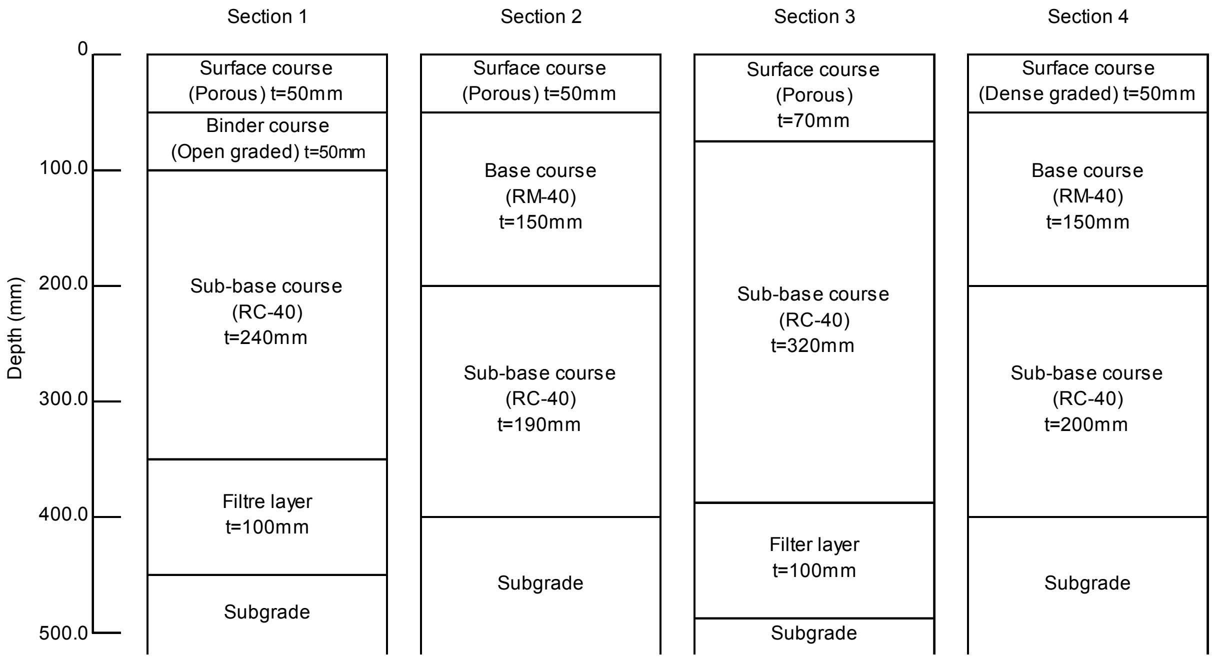


Figure 1 Structures of four types of pavements

b) Rainfall simulation

Rainfall simulation was performed as shown in Photo 1. The watering area was 25 m^2 (5m×5m). The boundaries of watering areas were sealed using liner sheets. The amounts of water

used are shown in Table 4. They are equivalent to the whole amounts of effective air voids in the pavements and are calculated using following equation.[5]

$$S = A \times F_s \times \Sigma (H_i \times V_i /100) \quad (1)$$

S : Amount of water (m^3)
A : Watering area (m^2), (A=25m^2)
H_i : Volume of each layer per road surface unit area (m^3/m^2)
V_i : Air voids in each layer (%)
F_s : Effective air voids ratio
(Ratio of air voids into which rain water actually goes to all the air voids) = 0.7

Photo 1 Rainfall simulation

Table 1 Characteristics of asphalt mixtures

Item	Permeable pavement		recycled dense-graded asphalt pavement
	Surface	Binder course	Surface
Percentage passing by mass (%)			
26.5 mm	-	100	-
19.0	100	96.8	100
13.2	95.1	60.8	98.6
4.75	26.9	21.3	63.2
2.36	18.6	18.1	47.8
0.6	12.6	9.9	29.3
0.3	9.0	8.1	19.9
0.15	6.0	6.3	8.8
0.075	4.9	5.2	5.7
Performance			
Air void (%)	17.7	19.4	3.5
Binder contents (%)	4.2	3.6	5.4

Table 2 Characteristics of granular materials

Item	RC-40	RM-40
Percentage passing by mass (%)		
53 mm	100	100
37.5	98.8	100
19.0	76.5	78
4.75	33.3	44.5
2.36	20.1	31.5
0.425	-	22.7
0.075	-	5.0
Performance		
Modified CBR value (%)	40.3	105.0
Air void (%)	18.6	-

Table 3 Characteristics of subgrade

Item	Section (Permeable pavement)		
	1	2	3
Soil	Sandy soil	Sandy soil	Sandy soil
CBR (%)	3.2	3.8	3.4

Table 4 Amount of water used in the experiment

Item	Section		
	1	2	3
Amount of water (m^3)	2.7	1.6	2.9
Amount of water per hour (mm/h)	30	30	40

c) Investigation procedure

FWD measurements were conducted before and after watering at the center of each experimental yard.

(2) Verification of change in bearing capacity

a) Change in bearing capacity

Figure 2 shows the D_0 deflection, i.e., the deflection of the loading center, before and after watering. Figure 3 shows the estimated CBR values of the subgrade (sections 1 - 3) in situ before and after watering. The estimated CBR was computed using formula (2).[6]

$$\text{Estimated CBR (\%)} = 1{,}000/D_{150} \tag{2}$$

D_{150} : Deflection 150 cm away from the loading center (μm)

From Figure 2 the D_0 deflection immediately increased slightly 10 to 15 minutes after watering. However, the estimated CBR did not change immediately after watering as shown in Figure 3. When rainwater existed in the pavements, the change in bearing capacity occurred above the subgrade. In this experiment, bearing capacity of the subgrade was not affected by infiltrated water.

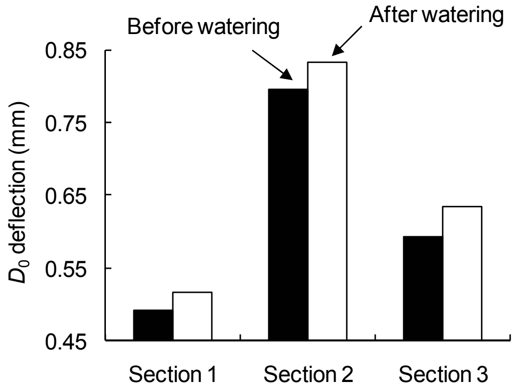


Figure 2 D_0 deflection before and after watering

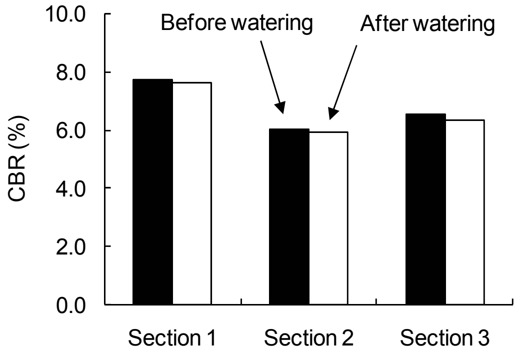


Figure 3 Estimated CBR before and after watering

b) Change in D_0 deflection with time

Figure 4 shows the change in D_0 deflection. Among sections 1 - 3, the D_0 deflection of section 2 was the largest. Although the deflection increased immediately after watering, the deflection after 70 hours was almost the same as that before watering.

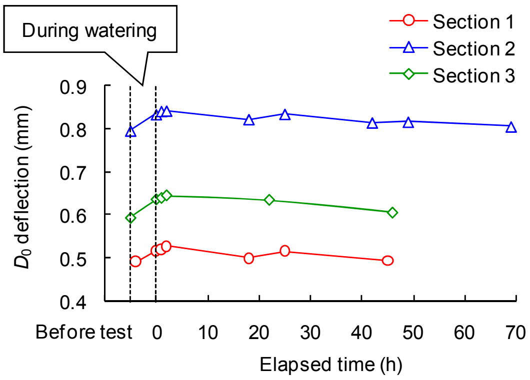


Figure 4 D_0 deflection

c) Evaluation of elastic modulus by back-calculation

Elastic modulus of each layer was estimated by back-calculation of FWD measurements. LMBS (Layer Moduli Backcalculation System), a back-calculation program available as freeware in Japan, was used. We back-calculated the modulus of the asphalt mixture, sub-base course and subgrade (including the filter layer). The elastic modulus of the asphalt mixture layer was corrected to the value at 20 °C using following temperature correction formula.[7] In the case of section 2, the base course and the sub-base course were treated as one layer.

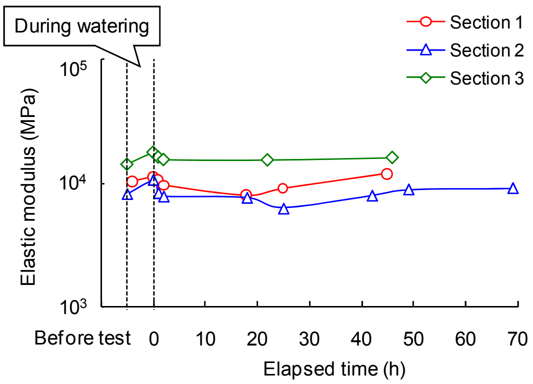
$$E_{as(20)} = E_{as(z)} \times 10^{(-0.0184 \times (20 - Tave(z))} \tag{3}$$

$E_{as(20)}$: Elastic modulus of asphalt mixture layer at a standard temperature of 20 °C (MPa)

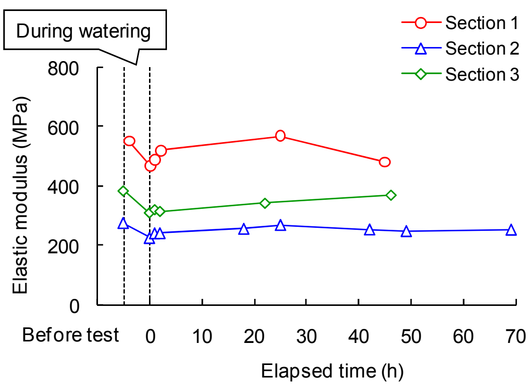
$E_{as(Z)}$: Elastic modulus of a T_{ave} °C asphalt mixture layer (MPa)

$T_{ave(Z)}$: Mean temperature of asphalt mixture layer at the time of FWD measurement (°C)

Figure 5 shows the results of the back-calculation of each layer. From Figure 5(c) the elastic modulus of the subgrade did not change between before and after watering. On the other hand, the elastic modulus of the base course decreased immediately after watering. Although the elastic modulus of section 2 and section 3 declined once, modulus returned gradually to the level before watering. Moreover, the elastic modulus of section 1 increased 18 hours after watering. The elastic modulus of the asphalt mixtures in each section was about 10^4 MPa, and it remained unchanged before and after watering. From this result, we concluded that when rainwater exists in permeable pavements, their bearing capacity reduces. However, although the bearing capacity recovers soon after, the long after value is slightly lower than the original value. The bearing capacity of each layer that reduced by infiltration of the water does not completely return to the first value. This result may become the decrease of the bearing capacity. From the back-calculation results, it was confirmed that decrease in the elastic modulus by water was remarkable especially in the granular sub-base course. In the following section, therefore, we focus on the performance of granular sub-base materials in the laboratory.

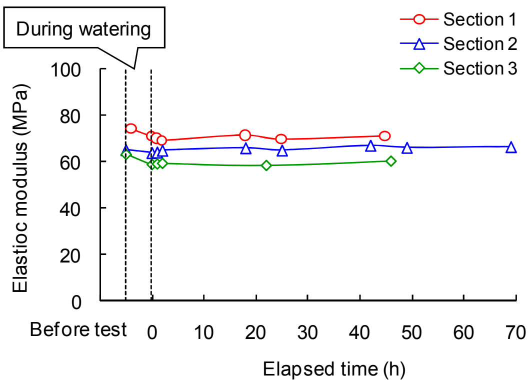


(a) Asphalt mixtures



(b) Granular materials

Figure 5 Back-calculated elastic modulus



(c) Subgrade

Figure 5 Back-calculated elastic modulus

3. Investigation of bearing capacity and permeability of granular materials in the laboratory

(1) Outline of the Experiment

a) Materials

Figure 6 shows the particle size distribution of the tested materials of RC-40. The test materials were made into three kinds such as upper, center, and lower gradation according to JIS (Japanese Industrial Standards).

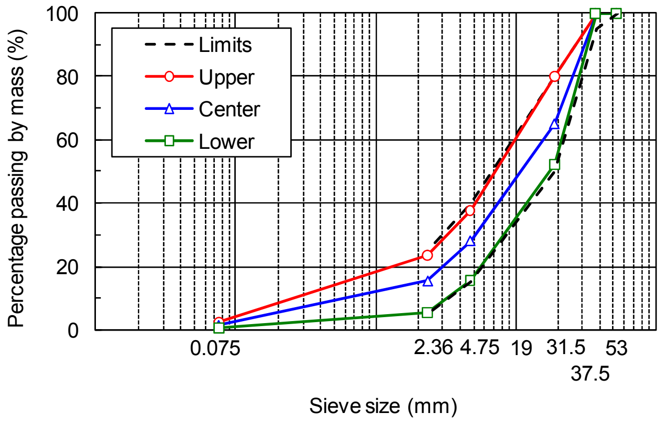


Figure 6 Combined gradation

b) Experiment item

Constant permeability tests and CBR tests were carried out.

c) Production of specimens

The material was compacted in a mold with a diameter of 150 mm and a height of 125 mm using an electric vibrating tamper at the compaction degrees of 95 % and 100%. Three specimens were prepared for each testing condition.

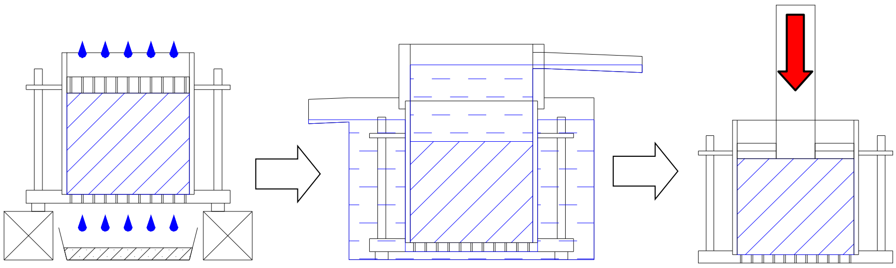
d) Experiment equipment

CBR test equipments were improved for water percolation tests and constant head permeability tests as shown in Figure 7.

e) Experimental procedure

Figure 7 and Photo 2 show the experimental procedure.

1) Water percolation was carried out as shown in Figure 7(a). Total amount of percolated water was prescribed to be 795 x 10^3 cm^3, which represents normal 30 years' precipitation in Japan. Fine grains, which passed thorough the bottom filter, were collected and measured the weight.
2) Water permeability test was carried out under constant head condition every 79.5 x 10^3 cm^3 of water percolation using an apparatus as illustrated in Figure 7(b).
3) After 795 x 10^3 cm^3 of water percolation, specimens were set in the loading machine and CBR tests were carried out as in Figure 7(c).



(a) Water passing through the specimen   (b) Water permeability test   (c) CBR test

Figure 7 Experimental procedure

(a) Water passing through the specimen   (b) Water permeability test   (c) CBR test

Photo 2 Experimental apparatus used in the tests

(2) Experimental results

a) Water permeability

Figure 8 shows the relation between the amount of water passing through the specimen and its coefficient of permeability. The plots show the average value of three specimens. Granular materials of lower gradation have the largest coefficient of permeability. There is no significant change in the

coefficient of permeability of each specimen during the course of the experiment (except upper gradation of 100% compaction). This change in the coefficient of permeability is a result of the fine grains to move downward due to seepage force. Figure 9 shows the relation between the void ratio before water percolation and the coefficient of permeability. The coefficient of permeability increases as the void ratio increases. Therefore, granular materials with center and lower gradation have higher permeability. Figure 10 shows the amount of materials that passed through the bottom filter. From the figure, it is confirmed that fine particles did not leak out by water percolation in the highly-compacted specimens.

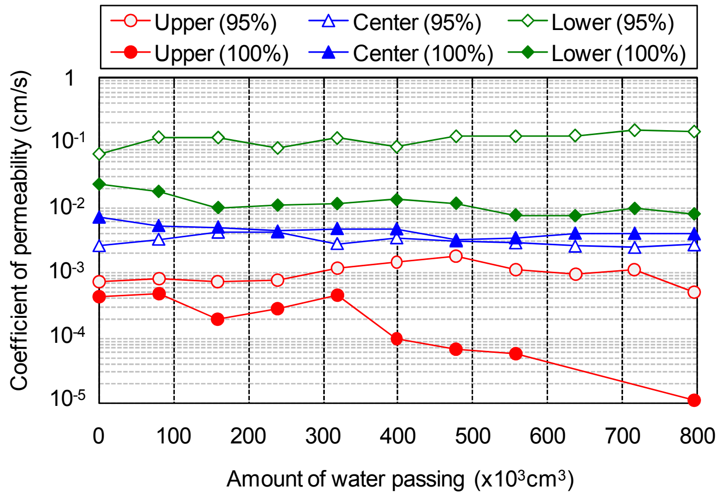


Figure 8 Change in coefficient of permeability

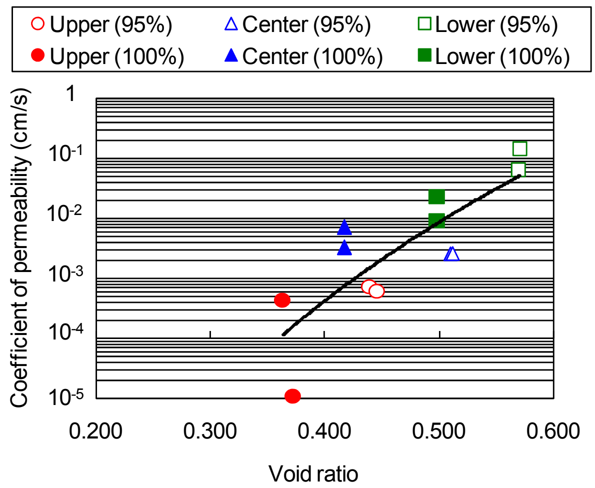


Figure 9 Relation between void ratio and coefficient of permeability

Especially, quantity of the fine grains leaked from the specimen with upper gradation was less than the specimens with other gradation. From these results, the fall of the aggregates with smaller grain size influences a ratio of aggregate forming a continuous air void facilitating the movement of the aggregates with smaller grain size.

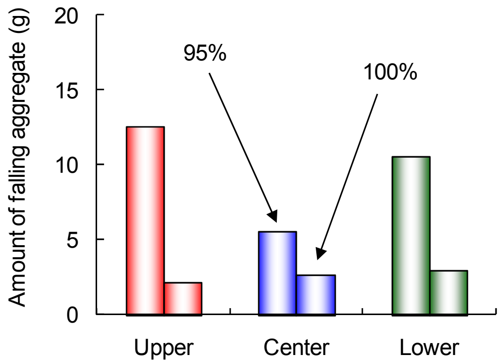


Figure 10 Comparison of amounts of minute grain

b) Change in bearing capacity

Figures 11 and 12 show the CBR values before and after watering. Before watering, the material with upper gradation has the largest CBR value, and the material with lower gradation has the smallest CBR value. After watering, the CBR value of all the materials decreases; however, the CBR value of the material with upper gradation is still the largest, and that of the material with lower gradation is still the smallest. The CBR value of the center and lower gradation of 95% compaction did not change. However, the CBR value of the upper gradation decreased. As a result, the change of bearing capacity would be influenced by the difference in gradation. And bearing capacity of the granular materials containing many fine aggregate would decrease. However, when the degree of compaction is 100%, the rate at which the CBR value decreases is the lowest for the material with upper gradation and the highest for the material with lower gradation. This might be the combined effect of the decrease in the void content of the aggregate, change in the aggregate matrix, and the degree of compaction. The effect of these factors was more pronounced in the material with upper gradation.

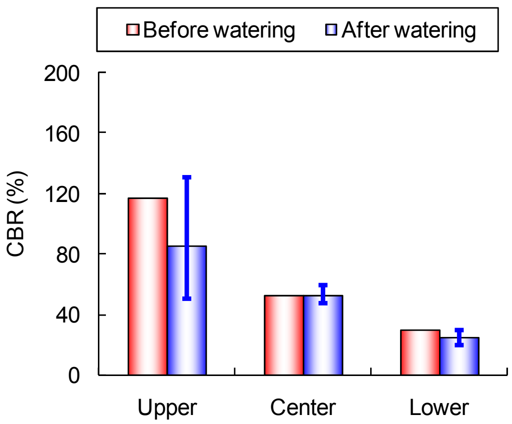


Fig.11 Change in bearing capacity (95%)

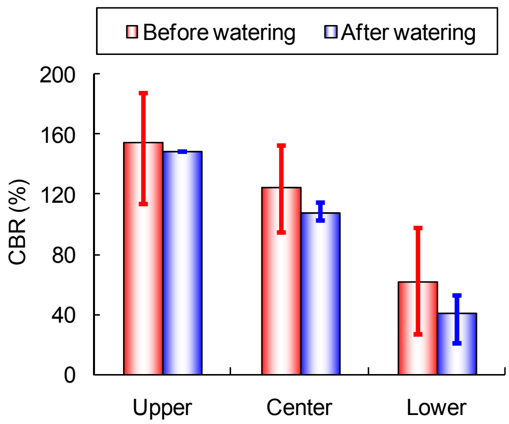


Fig.12 Change in bearing capacity (100%)

4. Conclusion

In this research, the change in the mechanical and hydraulic characteristics of permeable pavements due to infiltration of water was investigated by means of an actual road experiment and a laboratory experiment. In both types of experiments - actual and laboratory - we focused on the granular materials in permeable pavements. In the case of the actual road experiment, we observed that when water existed in the pavement, its bearing capacity changed before and after watering. During the laboratory experiment, we observed that a change in the gradation influenced the change in the bearing capacity by infiltration of water.
The results of our study can be summarized as follows.

(a) FWD measurements indicated the existence of water in a pavement affects the durability of the granular materials.
(b) The bearing capacity of the sub-base course material decreases due to infiltration of water. When the water drains into the subgrade, bearing capacity is recovered. However, although the bearing capacity recovers soon after, the overall value is slightly lower than the original elastic modulus.
(c) Laboratory experiment indicated the permeability of RC-40 does not decrease. However, for 100% compaction, the permeability of a material with upper gradation decreases.
(d) The CBR value of a material with upper gradation decreases considerably post water infiltration. Therefore, the gradation of granular materials is an important consideration as far as permeable pavements are concerned.

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